Interactive Visualizations for Teaching Quantum Mechanics and Semiconductor Physics

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***Abstract*—Work in Progress: The theory of Quantum Mechanics (QM) provides a foundation for many fields of science and engineering; however, its abstract nature and technical difficulty make QM a challenging subject for students to approach and grasp. This is partly because complex mathematical concepts involved in QM are difficult to visualize for students and the existing visualization are minimal and limited. We propose that many of these concepts can be communicated and experienced through interactive visualizations and games, drawing on the strengths and affordances of digital media. A game environment can make QM concepts more accessible and understandable by immersing students in nano-sized worlds governed by unique QM rules. Furthermore, replayability of games allows students to experience the probabilistic nature of QM concepts. In this paper, we present a game and a series of interactive visualizations that we are developing to provide students with an experiential environment to learn quantum mechanics. We will discuss how these visualizations and games can enable students to experiment with QM concepts, compare QM with classical physics, and get accustomed to the often counterintuitive laws of QM.**

Keywords—quantum mechanics; semiconductor physics; education; scientific visualization; games

I. Introduction

Quantum Mechanics (QM) is the foundation for numerous science and engineering disciplines, such as semiconductor physics, material science, and nanotechnology. However, educators face many challenges in introducing the concepts to beginners in the field. Unlike classical physics, students do not experience the laws of QM in their everyday lives; in fact, the laws of QM completely contradict everyday experiences. Students instead must gradually "get used to" thinking in terms of quantum physics, since they pertain to an environment that students have not actually experienced.

One of the main challenges in learning fundamentals of QM is the lack of embodied experience with the underlying physical concepts. A game or interactive simulation can provide a virtual world in which a player can experience and interact with the laws of QM. While video games have proven to be an effective educational tool for many engineering and science disciplines [1-4], very few exist that pertain to QM from a semiconductor physics standpoint, and the ones that do can be misleading. We feel that providing students with a responsive environment in which they can navigate and experience the laws of QM will enhance their understanding and active engagement with the topic.

In this paper we will discuss our ongoing development of a video game and a series of interactive visualizations that will provide students with a unique learning environment and can be used as lecture supplements for undergraduate students. These visualizations are designed to be easily accessible for students, visually and experientially engaging, and simple yet effective. They will provide students with the opportunity to experiment in an informal interactive environment, compare QM and classical physics, and be accustomed to the principles through replayability and exposure. We will also be proposing research methodologies for evaluating the effectiveness of our designs.

II. Problem

A. Contradicting Students' Existing Conceptual Models

There are numerous factors that affect the difficulty of teaching QM as opposed to other topics in science. In many cases, the laws of QM directly contradict students' preconceived notion of classical physics, which makes it harder for the students to approach the topics. We can see how students' constant exposure to classical physics can affect their knowledge in QM from Müller and Wiesner's study conducted from 1996-1998. They aimed to analyze students' knowledge of quantum mechanics after these students have taken one class on QM. When asked about their conception of the atomic model, 41% of 523 of the participating students mistakenly attribute Bohr's model of an atom to be an accurate representation of an atom. Bohr's model depicts electrons in "orbit" around the nucleus, not unlike planets around the Sun, and is taught repeatedly in early science education. One student even mentions "One is told that it's not correct, but one is so used to it and, after all, it is employed again and again" [5]. It can be concluded that the Bohr Model is a widely accepted and easily interpreted model of an atom that causes difficulty in an understanding of QM.

B. High-Level Mathematical Concepts

Students usually do not reach an introductory course in QM until they begin their undergraduate studies in a scientific field. Traditionally, these students would learn QM in a more theoretical light and be given the high-level mathematical concepts before being able to visualize these concepts [6].

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Müller and Wiesner devised a course that teaches QM topics at a conceptual level, emphasizing features of QM that differ greatly from classical mechanics and de-emphasizing mathematical theory with the aim of reducing confusion between classical and quantum physics. They stripped out the formal, mathematical side of QM so students could solely focus on qualitative reasoning. The results from the experiment were positive: in the tests comparing the experimental group (the students who participated in the introductory course) with the control group (students who were instructed in physics using the traditional method), the experimental group tested higher than the control group in every category evaluated. The test contained qualitative questions such as "In principle, quantum objects can possess simultaneously position and momentum" and used a Likert scale to assess each student's' understanding of the topic. An introduction to QM should therefore focus on differences from classical physics rather than mathematical concepts [5].

C. *Visualizations and Misconceptions*

Since QM is rooted in abstract probabilities, one of the main challenges is: "How do we visualize probability?" QM is about making statistical predictions based on many measurements. Students must understand that a precise position of a particle cannot be predicted, but the probability of finding it in any region can be inferred from its wave function. Visualizing this concept is a challenge, as the nature of illustrating abstract concepts allow for multiple interpretations. We can also see misconceptions occurring in scientific visualizations due to exaggerations and different points of view employed to convey something that is otherwise hard to visualize [7]. When used in teaching, different analogies of an idea may cue students to infer different characteristics of the concepts being communicated [8]. One example of a common QM visualization that frequently misrepresents the probabilistic nature of QM comes from the depiction of probability versus probability density of an electron. Take the case of an "s" orbital in a hydrogen atom. In a probability density electron cloud diagram, we see that there is a concentrated cloud at the Bohr radius of the hydrogen atom, and it is implied that there is a high probability of finding the electron at that Bohr radius. At the same time, this is implying that if we were to take an arbitrary cubic volume near the Bohr radius and compare it to a similar volume closer to the nucleus, we would see a higher probability of finding the electron in the volume at the Bohr radius. This is not true. When the volume is similar, the probability becomes higher near the nucleus. This visualization may be useful in communicating some aspects, but also easy to be misinterpreted as representing density.

III. Learning Through Gameplay

Games are also a promising medium to demonstrate QM concepts. Video games frequently provide their audience with a visual fantasy world unlike anything they have experienced in reality. Players quickly learn to explore the environment and to live by the rules established by the game. Games allow players to become immersed in new worlds and live by new rules in a compelling and exploratory fashion. Furthermore, in games, complex tasks can be presented as a series of smaller, more focused tasks that can be learned and practiced progressively [2]. This "concurrent chaining" approach has proven a more effective learning method compared to whole-task learning [9].

Podolefsky et al. looked into introducing the notion of play into the classroom in one of their experiments. They set up two 5th grade classrooms that utilize a computer simulation for light refraction. One class began with an open play session where the students were encouraged to freely explore the simulated environment, and the other just performed a written activity that utilized the simulation. The classroom that encouraged open play time were more likely to be engaged in the topic, and were more open and asked more questions [10]. Although the experiment was undertaken on a younger audience than we are targeting, the implications still stand. Playing with a simulation gives the students a sense of voluntary involvement that could provide intrinsic motivation and more sustained engagement. Rieber compared the act of play to a scientist's approach to tackling a new and unfamiliar problem [11]. Among attributes of play that contribute to learning are intrinsic motivation, active engagement, experimentation, and replayability.

IV. Existing Designs

We researched several existing visualizations—both static and interactive—to see whether they address the problems noted above.

Quantum Tic-Tac-Toe is a web game designed to show the counterintuitive nature of quantum superposition. The gameplay is based on the familiar, classic game of tic-tac-toe and is intended to be easily approachable for newcomers to physics, requiring no mathematical training. Goff states that Quantum Tic-Tac-Toe provides metaphors that open up the field of QM for students [12]. However, they cover topics of QM that do not directly pertain to the field of semiconductor physics, nor does it explain other fundamental QM principles such as the atomic model.

We also looked at a series of visualizations, called "Visual Quantum Mechanics". This is a collection of Mathematica-generated online movies that show QM phenomena. These visualizations are designed to be more comprehensive than conventional textbook material and provide colorful ways to visualize many concepts in both two and three dimensions [13]. These visualizations are not effective for newcomers in the field however, as they are mathematically complex and do not utilize real-world metaphors.

V. Proposed Design Concept

One of our design concepts is a game that depicts an interactive world based on the common particle-in-a-box thought experiment of QM. Traditionally, the particle-in-a-box problem is depicted by a static representation of a standing wave inside of a 2D box as shown in Fig. 1.

This game introduces elements of time, interactivity, and a reward mechanism into the traditional presentation of the particle-in-a-box, thus creating a novel way to introduce it to beginners in the field. In this game, we aim to highlight the differences between physical properties of objects in classical

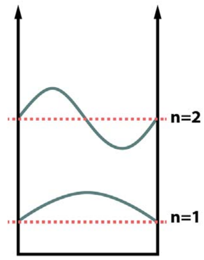

Figure 1. Particle-in-a-box depiction of the first two energy states of a particle's wave function.

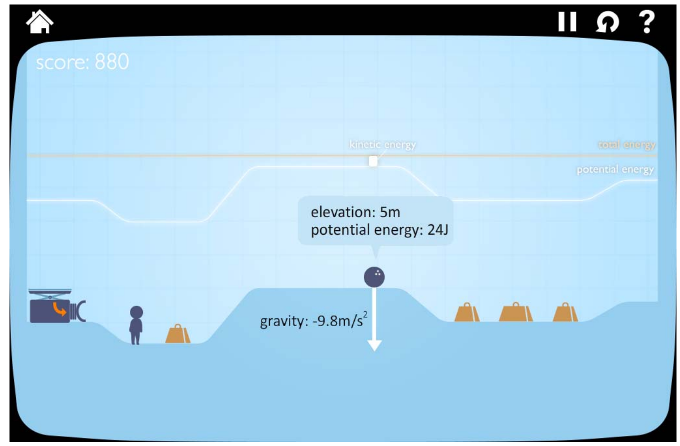

Figure 2. Classical Physics mode of the particle-in-a-box simulation.

physics and the unpredictable nature of quantum physics. The game uses common objects as metaphors for the classical physics mode and abstract images for the quantum physics mode—a bowling ball for the former and a plasma sphere (representing an electron) for the latter. These representations are chosen to show a sense of scale for the bowling ball and a sense of fantasy for the electron. We designed two very distinct environments that allow students to contrast the properties in classical physics with those of quantum mechanics.

The basic gameplay is as follows: the player controls an avatar walking in one dimension of a 2-dimensional environment. This environment begins in the "classical physics mode" which presents a ball that is moving back and forth and several weights of different sizes placed in the stage. If the player's avatar makes contact with the ball, the player has been "hit" and is sent back to the beginning of the stage. The objective is to collect all of the weights and bring them to a pre-designated area called the Starting Zone while avoiding being hit by the ball. The act of returning a weight to the Starting Zone will increase the energy of the ball, causing the ball to reach higher altitudes in the game. This game mechanic invites the player to pay special attention to the potential, kinetic, and total energies that are also depicted as graphs in the background of the game. The potential energy in this case simply follows the elevation of the stage. We use a faint white color for energy plots in the background to distinguish them from real objects such as the bowling ball or the playing field. In addition, there is a variation in size of collectable items—as the size of a collectable item increases, the probability of the bowling ball colliding with the player increases. These both aim to help the player experience probability through the likelihood of encountering danger, and learning occurs through experienced play. The environment of the classical physics mode closely mirrors everyday experience of physical objects. Players' attention is directed toward the concepts of potential and kinetic energies, conservation of energy, predictability of position and momentum, the continuous nature of allowed energies and the fact that a ball cannot reach certain regions because of its finite energy.

Next, moving into the "quantum physics mode", the player is presented with the quantum world. Both the environment and gameplay are familiar yet different in this mode; similarly to the classical physics mode, the player's goal is to avoid a ball (this time an electron). However, the position of the electron is unknown until a measurement is made and its probability density function depends on the electron energy. In addition to the total and potential energies, the electron wave function is also displayed in the background and its amplitude squared represents the probability density function. In this mode, the player is collecting light bulbs which can shine photons and excite electrons to higher energy levels. Bringing the light bulbs to the Starting Zone increases the energy of the electron to the next quanta; the electron's wave function has now reached the next quantized state. Every few seconds a "measurement" will be taken, revealing the electron's new location. In this quantum world, rules are unfamiliar. Only probabilities are known. Energies are quantized, and electrons can tunnel through potential barriers. In both the classical and quantum environments, the potential energy can be changed; it varies naturally in the classical world and in the quantum world it is changed by moving around some stationary positive charges.

In the next phase of the design, we plan to include periodic tutorials throughout the game to provide contexts to the scientific principles and vocabulary that exist in the game. These also inform the player of the gameplay goals in different aspects of the game.

The game is implemented in JavaScript using the CraftyJS game engine. Through Crafty the game leverages modern web technologies present in HTML5 such as the "canvas" tag. The portions of HTML5 used along with CraftyJS itself are sup-

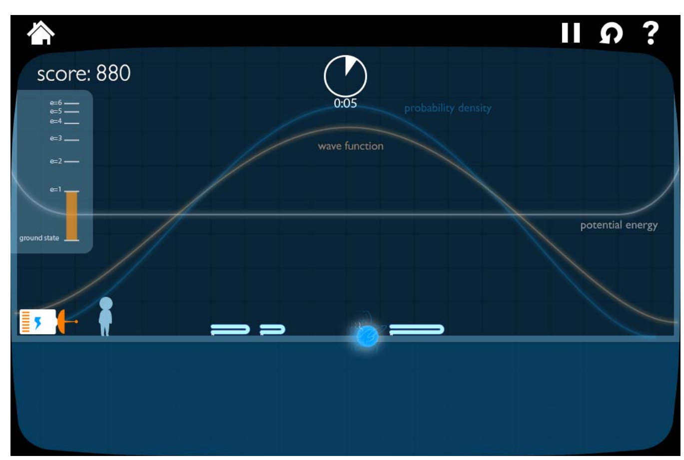

Figure 3. Quantum Physics mode of the particle-in-a-box simulation.

ported in all modern browsers. Most mobile browsers are supported as well allowing the game to be played on many modern devices such as smart phones and tablets.

The game determines the energy levels and wave equations for varied potential profiles by solving the one-dimensional time independent Schrödinger equation using the the finite difference method (FDM). Additionally, the potential profiles used in the game all occur in infinite potential wells; the Dirichlet boundary conditions for an infinite well are naturally represented by FDM.

VI. Future Work

A. Research Methodology

We will be conducting a series of evaluations to determine the effectiveness of our visualizations in teaching QM. Our hypotheses state that students will find an interactive environment to be more engaging as a learning tool than non-interactive environments; that the visualizations will enable students to conceptually grasp QM principles and that a correlation will be found between students who spend time playing this game and their retention of knowledge of QM laws and concepts.

To test the above hypotheses, the game and visualizations will be integrated into an undergraduate microelectronics courses as a supplement to course lectures. A control group will be set up in a similar class, but without the interactive environments and games integrated in. The experimental group of students will learn the abstract topics that the visualizations cover and be encouraged to play the game and experiment in the semiconductor physics visualizations. In addition to providing the opportunity for students to play the games, we will evaluate the effectiveness of the games through observation of playing patterns, whether or not the players improve their scores by better learning the laws of the game, and how long they play. Both groups will be interviewed to compare their understanding of QM concepts. We will also look to see if gameplay patterns emerge from the evaluation data (e.g., how often students play the game and how long each playthrough takes).

B. Semiconductor Physics Visualizer

In addition to the particle-in-a-box game, we are designing a series of visualizations that showcase a silicon lattice structure of a semiconductor. With these visualizations we aim to tell a story connecting the electron cloud model of a Hydrogen atom to the larger context of a silicon lattice, which will help to explain the role of QM in semiconductor physics. The visualizations begin with an 's' orbital in a hydrogen atom. An animation will show one electron mapped in a spherical orbit, and as it appears and disappears in the space around the nucleus, eventually we begin to see a map of the most probable locations to find the electron. We then aim to solve the problem of misleading information in this model by charting a graph of the probability density in relation to the volume of electron locations at each orbit around the nucleus, depicting the radial probability distribution. If this is displayed correctly, we will see that the electron is more likely to be found at the Bohr radius of the hydrogen atom.

In subsequent visualizations in this series, we will build representations of other concepts such as orbital shapes of a silicon atom, photon excitement of an electron, electron holes, structure of a silicon lattice, doping of a lattice, etc. As these concepts become more and more complex, we will sustain player engagement by introducing new challenges and new ways to interact in these environments.

VII. Conclusion

QM is a difficult topic to teach and many different attempts have been made to approach this daunting task. Our work-in-progress study aims to devise a novel approach to teaching QM to beginners in the field through games and play. We will do this by tackling formal abstract concepts and visualizing them in interactive worlds that will be enjoyable as well as informative.

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